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Research Article

The Grassland Butterfly Index for Germany

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Abstract

In 2024, the European Union implemented its Nature Restoration Regulation (NRR) to restore degraded ecosystems and to reverse the loss of biodiversity. One of the objectives is to increase biodiversity in agricultural systems. To measure progress towards this goal, Member States need to report two out of three indicators, one of which is the Grassland Butterfly Index (GBI). The GBI represents a composite index which combines the trends of 17 butterfly species, some widespread and some more specialised, considered as typical for grassland habitats across Europe. The aim of the present study was to calculate a first version of the GBI for Germany using data collected within the German butterfly monitoring scheme from 2006 to 2023. For this purpose, two methodological approaches were applied: (1) the approach prescribed by the NRR (EU 2024) and (2) an alternative approach which includes other frequently applied methods to analyse time series from biodiversity monitoring schemes. Depending on the methodological approach, the GBI showed a stable development (approach 1) or a moderate decline (approach 2) over the entire study period. Both approaches, however, showed a significant decline over the last 10 years, which mainly seems to be a result of low butterfly abundances in recent years. A closer examination of the underlying species trends indicated that habitat specialists tended to suffer most from declines. These results largely correspond to patterns found in other regions and at the European scale and suggest that butterflies inhabiting agricultural systems are under threat. However, the reasons for the negative trends require further research. There is also a clear need to improve the representativity and robustness of the indicator at the national scale. Several options for expanding monitoring and widening the data basis are discussed.

Key words: Agriculture, butterfly monitoring, grasslands, Nature Restoration Regulation, pollinators

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Introduction

Ecosystem restoration has become one of the most important strategies for halting the decline of biodiversity and maintaining essential ecosystem services (IPBES 2018; UNCCD 2022). Recognising the urgency of this issue, various global commitments have set explicit restoration targets. One of the

most significant is the Kunming–Montreal Global Biodiversity Framework under the Convention on Biological Diversity, adopted in 2022 (http://www.cbd.int/gbf/). This framework sets long-term restoration goals for 2050, with specific milestones to be achieved by 2030. At the European level, the EU's Nature Restoration Regulation (NRR) (EU 2024), which recently came into force, serves as a key component to achieve the goals of the EU Biodiversity Strategy for 2030 (EC 2020). This regulation requires EU Member States to develop national restoration plans and to implement restoration measures in terrestrial, freshwater, coastal and marine habitats.

Agricultural systems are amongst the most degraded ecosystems globally (Barnosky et al. 2011; Cowie et al. 2022). The intensification of agricultural practices has led to habitat loss, landscape homogenisation and the decline of a large number of species that rely on semi-natural habitats (EEA 2020). At the same time, agricultural productivity is directly linked to biodiversity, as essential ecosystem services, such as pollination, pest control and nutrient cycling, are crucial for food security (Garibaldi et al. 2016; Dainese et al. 2019). Under the Nature Restoration Regulation, EU Member States are required to implement restoration measures that enhance biodiversity in agricultural systems, while considering the economic and social needs of rural communities, climate change and the sustainability of agricultural production (Article 11). To track progress, indicators have been defined to monitor ecosystem recovery. Specifically, the NRR requires Member States to achieve increasing trends in at least two of the following three indicators at the national level until satisfactory levels are reached: (1) Grassland Butterfly Index; (2) Stock of organic carbon in cropland mineral soils and (3) Share of agricultural land with high-diversity landscape features (Article 11). This study outlines two methods how the Grassland Butterfly Index (hereafter referred to as GBI) can be calculated for Germany, using extensive data from a volunteer-based monitoring programme.

For a long time, butterflies have been used as bioindicators due to their sensitivity to environmental changes and their rapid response to habitat alterations (Nowicki et al. 2008). Their strong dependence on specific plant species and microhabitats, especially for their larval development, makes them particularly vulnerable to land-use changes, agricultural intensification and climate change (Habel et al. 2021; Montràs-Janer et al. 2024). The United Kingdom was the first country to establish a nation-wide butterfly monitoring programme in 1976 with the launch of the UK Butterfly Monitoring Scheme (UKBMS; https://ukbms.org/). This early initiative laid the foundation for similar programmes across Europe, with countries like the Netherlands, Belgium (Flanders) and Spain (Catalonia) developing their own monitoring schemes in the 1990s (Van Swaay et al. 1997). In Germany, the national butterfly monitoring scheme (Tagfalter-Monitoring Deutschland, hereafter called TMD) was launched in 2005 with the aim of tracking butterfly populations across the entire country. Since then, these efforts have generated valuable long-term data that contribute to national and European-wide biodiversity assessments.

The European GBI was first developed to measure progress towards the European Unions´ target to halt the loss of biodiversity until 2010 (Brereton et al. 2009). This indicator is regularly updated (last update by Van Swaay et al. (2025)) and serves as a biodiversity indicator of the European Environment

Agency to support environmental policy-making (https://www.eea.europa.eu/en/analysis/indicators/grassland-butterfly-index-in-europe-1). The GBI is based on a group of 17 butterfly species that have been selected by experts for their association with semi-natural grassland habitats. These species are considered as reliable indicators of grassland ecosystem health due to their strong dependence on open grasslands, making them particularly sensitive to habitat degradation and changes in land-use. Recent calculations of the European Grassland Butterfly Indicator (Van Swaay et al. 2025) show a considerable decline in grassland butterfly populations, with an overall decrease of approximately 50% in the EU from 1991 to 2023. Van Swaay et al. (2025) attribute this decline primarily to habitat loss resulting from grassland intensification and nitrogen deposition, pesticides and abandonment, with the importance of these factors varying markedly between individual European regions. Species that depend on nutrient-poor grasslands have been disproportionately affected, indicating a continued degradation of semi-natural habitats (Habel et al. 2019a; Van Swaay et al. 2019).

Currently, the Grassland Butterfly Index is not yet widely available at the national level in most EU Member States. Exceptions are Sweden (Pettersson and Arnberg 2024), the Netherlands (Van Swaay and Borkent 2025), Luxembourg (Vray et al. 2024) and Catalonia (GENCAT 2024), where national versions of the GBI have been developed, based on data from long-term monitoring programmes. This study aims to calculate the Grassland Butterfly Index for Germany using data from the national volunteer-based monitoring scheme and by applying two alternative methods. The results will also be used to discuss the indicator's strengths and limitations in contributing to future biodiversity monitoring and restoration efforts in agricultural landscapes.

Materials and methods

Butterfly monitoring

The Butterfly Monitoring Germany (TMD) is a citizen-science programme designed to track population trends of butterflies across Germany. Butterflies are excellent bioindicators due to their short generation cycles, specific habitat requirements and relative ease of identification.

The TMD primarily employs the line-transect method (Pollard 1977). This standard approach involves volunteers selecting a fixed transect route of up to 500 m in length, divided into 50 m sections. Observers ideally conduct weekly surveys from April to September, recording all butterflies encountered within a 5 × 5 × 5 m box moving along the transect. Environmental conditions, such as temperature, wind and cloud cover, are also documented, as they significantly influence butterfly activity (but see Lang et al. (2025)). Until today, over 1000 volunteers have participated in the scheme, spread all over Germany (see Fig. 1), contributing to the most extensive time series on butterfly populations in Germany. This is also reflected in the pure key figures: In the years 2005–2023, more than 1600 transects were established; on more than 130,000 transect walks, ~4.4 million butterflies have been recorded (Kühn et al. 2025).

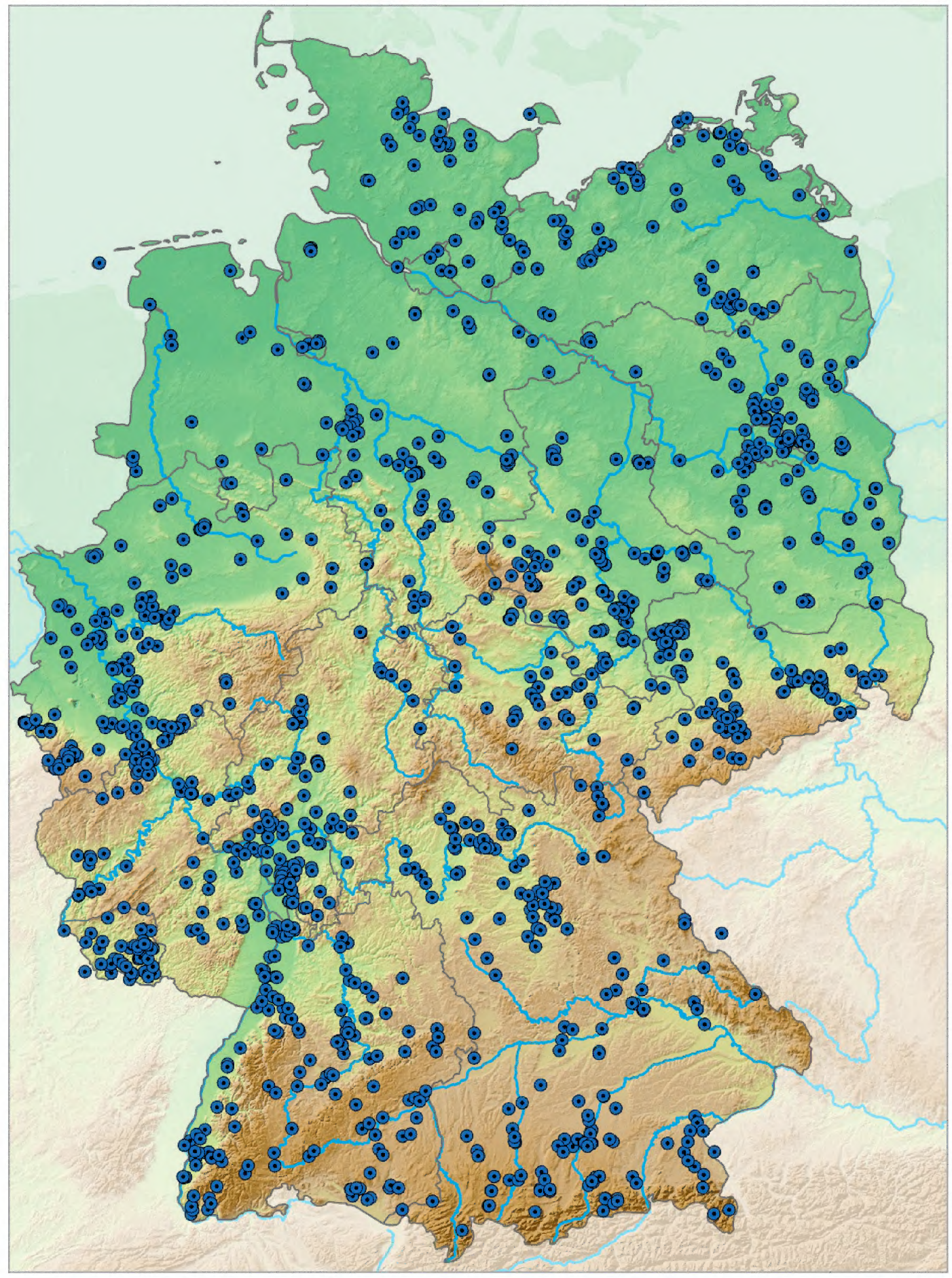

Figure 1. Distribution of transects established in the German BMS.

The TMD is integrated into the European Butterfly Monitoring Scheme (eBMS), which coordinates standardised butterfly monitoring across more than 30 European countries (incl. all EU27 countries; https://www.ufz.de/spring-pollination/index.php?en=49053). Currently, eBMS is the only pan-European monitoring network for invertebrates and pollinators and the GBI is the only established indicator for assessing their status and trends at this scale. All national butterfly monitoring schemes follow the same standardised methodology, allowing for international comparisons and large-scale biodiversity assessments. There is flexibility only in terms of the frequency of recording and the length of the transects. Each year, the TMD data contribute to the eBMS database, which is managed in partnership with Butterfly Conservation Europe (BCE) and used to analyse long-term trends in butterfly populations across the continent.

Species selection

The grassland butterfly index that has been retained for the NRR is based on the European butterfly indicator for grassland species (Van Swaay et al. 2025). It consists of a multispecies index that integrates the trends of 17 species considered typical for various types of grasslands across Europe. Amongst the selected species, seven are widespread species and ten are habitat specialists (Table 1). Although all 17 species occur in Germany and are covered by TMD, only 15 species had enough data to be included in the German grassland butterfly index. The data available for the Large Blue (*Phengaris arion*) and the Marsh Fritillary (*Euphydryas aurinia*) were too scarce to estimate reliable population indices and trends.

Table 1. Species and the extent of data available in the TMD to provide information for the grassland butterfly index in Germany.

Species	Category	Total number of transects included in analysis	Species included in analysis
Ochlodes sylvanus (Esper, 1777)	widespread species	423	yes
Anthocharis cardamines (Linnaeus, 1758)	widespread species	597	yes
Lycaena phlaeas (Linnaeus, 1761)	widespread species	455	yes
Polyommatus icarus (Rottemburg, 1775)	widespread species	631	yes
Lasiommata megera (Linnaeus, 1767)	widespread species	171	yes
Coenonympha pamphilus (Linnaeus, 1758)	widespread species	650	yes
Maniola jurtina (Linnaeus, 1758)	widespread species	745	yes
Erynnis tages (Linnaeus, 1758)	specialist species	104	yes
Thymelicus acteon (Rottemburg, 1775)	specialist species	19	yes
Spialia sertorius (Hoffmannsegg, 1804)	specialist species	14	yes
Cupido minimus (Fuessly, 1775)	specialist species	44	yes
Phengaris arion (Linnaeus, 1758)	specialist species	7	no
Phengaris nausithous (Bergsträsser, 1779)	specialist species	28	yes
Lysandra bellargus (Rottemburg, 1775)	specialist species	71	yes
Lysandra coridon (Poda, 1761)	specialist species	60	yes
Cyaniris semiargus (Rottemburg, 1775)	specialist species	129	yes
Euphydryas aurinia (Rottemburg, 1775)	specialist species	4	no

Annual abundance indices

For many volunteers, it is often not possible to conduct weekly transect walks. Therefore, time series, based on transect walks, often contain missing weekly counts. This makes it difficult to estimate annual abundance indices, as the short flight time of many butterfly species cannot be optimally covered. In the present study, annual abundance indices were estimated for each species, site and year (hereafter called “site index”) using the two-stage modelling approach, developed by Dennis et al. (2013) which is implemented in the R package rbms (Schmucki et al. 2024). This approach accounts for the pronounced seasonality of butterflies and allows the inclusion of data with missing weekly counts. First, an annual flight curve for each species was estimated across all sites using a generalised additive model (GAM) with a Poisson error structure,

with weekly counts fitted as a function of a site effect and a smoothing spline on week. In the analysis, only counts carried out in the time frame 1 April to 30 September were included. In a second step, missing weekly counts were estimated by applying an arithmetic interpolation approach, using the standardised annual flight curve and the observed counts to estimate and impute the missing values. Finally, a site index was calculated as the sum of observed and imputed weekly counts over the sampling season. To obtain reliable estimates, only sites with a minimum of five visits per season were included in the calculation of the flight curve. If the site visits covered less than 10% of the flight period of a given species in a given year, the respective site index was not used in subsequent analyses.

Species trends and Grassland Butterfly Index

Abundance indices obtained from the modelling procedure as described above were used to calculate collated indices, species trends and multi-species indices. For this purpose, two alternative approaches were applied. To reduce potential undesired effects of missing values, only sites with a minimum of three positive site indices were included in the analysis of species trends analysis and multi-species indicators.

Approach 1

First, we followed the methodological framework as described by Van Swaay et al. (2025), which also reflects the methods prescribed by Annex IV of the NRR. Using a non-parametric bootstrapping approach, site-level abundance indices were first randomly re-sampled 1000 times while keeping the number of transects sampled per year the same as in the original data. For this purpose, the function boot_sample from the R-package rbms was used. This bootstrapping approach was applied to account for various sources of uncertainty (Dennis et al. 2013). Collated indices per species and year were then calculated by fitting a Poisson Generalised Linear Model (GLM) with site and year effects on site-level abundance indices. By applying the model to each bootstrap, it was possible to compute a 95% confidence interval around the collated index. Species trends were estimated by applying a linear regression model to the collated indices. To quantify uncertainty, the model was applied to each bootstrap. Species trends were classified according to the classification scheme of Pannekoek (2005) and annual rates of change were obtained from the slope of the linear regression models.

The Grassland Butterfly Index was calculated as the geometric mean of species collated indices. The geometric mean represents a commonly used metric to build composite biodiversity indices (Butchart et al. 2010; Buckland et al. 2011). Well-known examples are the Living Planet Index (Collen et al. 2009), the European bird indicators (Gregory and van Strien 2010; Gregory et al. 2019) and the European Grassland Butterfly Indicator for grassland species (Van Swaay et al. 2025). When positive and negative trends are balanced, the geometric mean remains stable. It increases when species with positive trends dominate over species with negative trends and vice versa. A smoothed indicator was obtained by fitting a LOESS regression as described by Soldaat

et al. (2017). This procedure was applied to each of 1000 bootstraps from which the quantiles were used to calculate 95% confidence intervals around the indicator. To estimate the trend, a linear regression was applied. Confidence intervals of the trend were obtained by applying the linear model to each bootstrap sample. The R code for calculating annual abundance indices, collated indices, species trends and multi-species indices is available from Schmucki et al. (2020).

Approach 2

As an alternative, species trends and their standard errors were estimated using log-linear regression models as provided by the R package rtrim (Bogaart et al. 2024), a widely used standard tool to analyse time series from biodiversity monitoring schemes (e.g. Lehikoinen et al. (2019); Wotton et al. (2020)). The implemented Generalised Estimated Equations approach allows for the correction of over-dispersion and serial correlation of site indices. As with many volunteer-based monitoring programmes, TMD time series are incomplete for many sites. The modelling approach implemented in rtrim interpolates missing site indices by using information on index changes from all other sites. Apart from the trend, this procedure provided species-specific population indices along with their standard errors which were used in the subsequent analysis to construct the Grassland Butterfly Index.

The Grassland Butterfly Index was calculated as the geometric mean of individual species indices derived from rtrim using the MSI (multi species index) tool developed by Soldaat et al. (2017). This tool considers the sampling error of the underlying species indices by calculating confidence intervals using Monte Carlo (MC) simulations of the species indices. Each available yearly species index was simulated 1000 times. Simulated species indices were standardised to 2006 as a common base year and an MSI was calculated for each simulation. From the 1000 MSIs per year, mean annual MSIs and standard errors were calculated. Each annual MSI was then simulated 1000 times, again using an MC procedure. Based on these simulations, a linear trend was estimated using OLS regression and a smoothed trend using LOESS regression. Linear trends were estimated and classified according to Soldaat et al. (2017) for the entire study period (2006–2023) and for the last 10 years (2013–2023). Mean annual percentage change for both periods was derived from linear trend estimates (multiplicative slopes).

Results

From 2006 to 2023, the linear trend of the Grassland Butterfly Index was classified as stable (-0.7% per year, n. s.) when using Approach 1 and a moderate, but significant decline when using Approach 2 (Fig. 2). The decline revealed by Approach 2 corresponds to a mean change of -0.66% per year. While the two approaches resulted in a different assessment of the overall trend, both were consistently negative over the last ten years. During this time frame, the index changed by -2.82% (Approach 1) and -3.26% (Approach 2) per year, which corresponds to a “moderate decline” according to the classification scheme of Soldaat et al. (2017).

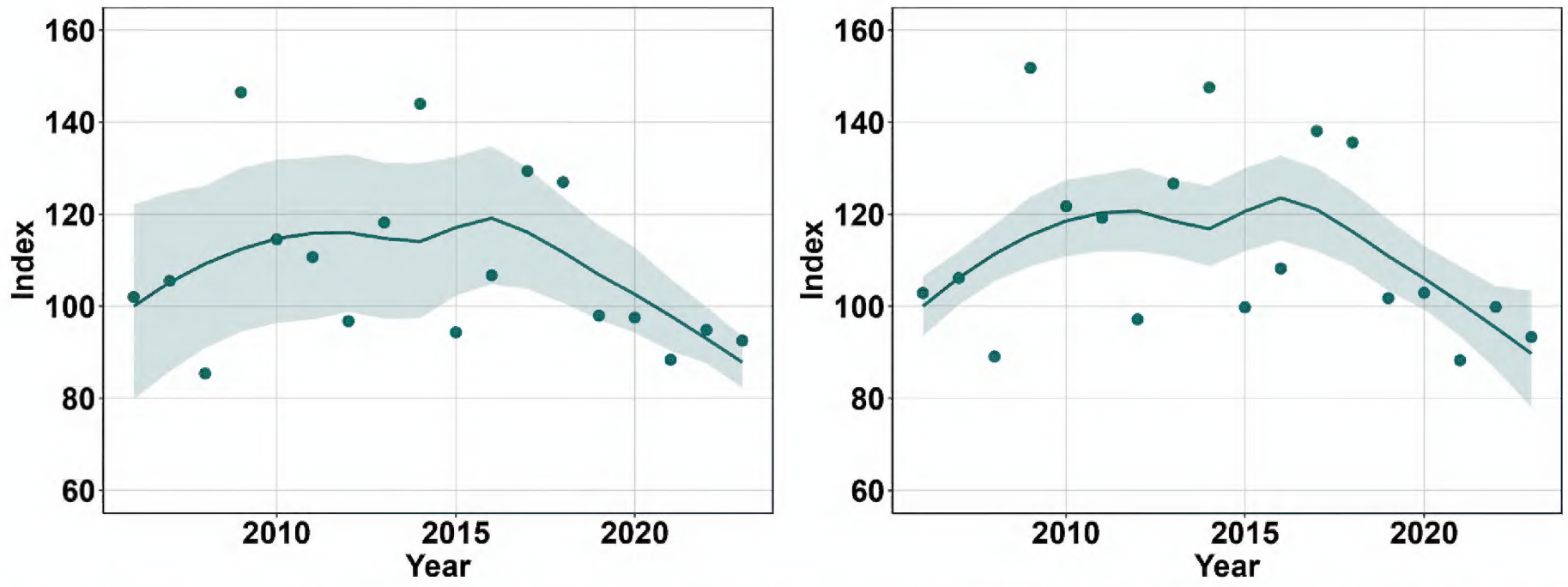

Figure 2. Development of the German Grassland Butterfly Index 2006–2023, based on German Butterfly Monitoring Scheme data using Approach 1 (left) and Approach 2 (right). The annual index values (points) and the smoothed trend with 95% confidence intervals are shown.

Using Approach 1, four of the 15 species included showed a moderate increase ($p < 0.05$) and five a moderate decrease ($p < 0.05$) (Fig. 3). The trend of six species was uncertain, which likely reflects the small sample size in some species and large variation amongst sites. Positive trends were restricted to widespread species; negative trends were found in both specialist and widespread species. Change rates obtained from Approach 2 were very similar to those of Approach 1, but trend models implemented in rtrim resulted in more significant trends. While six species showed a positive trend, it was negative for seven species (Fig. 3). The trends of two species were classified as “stable” or “uncertain”.

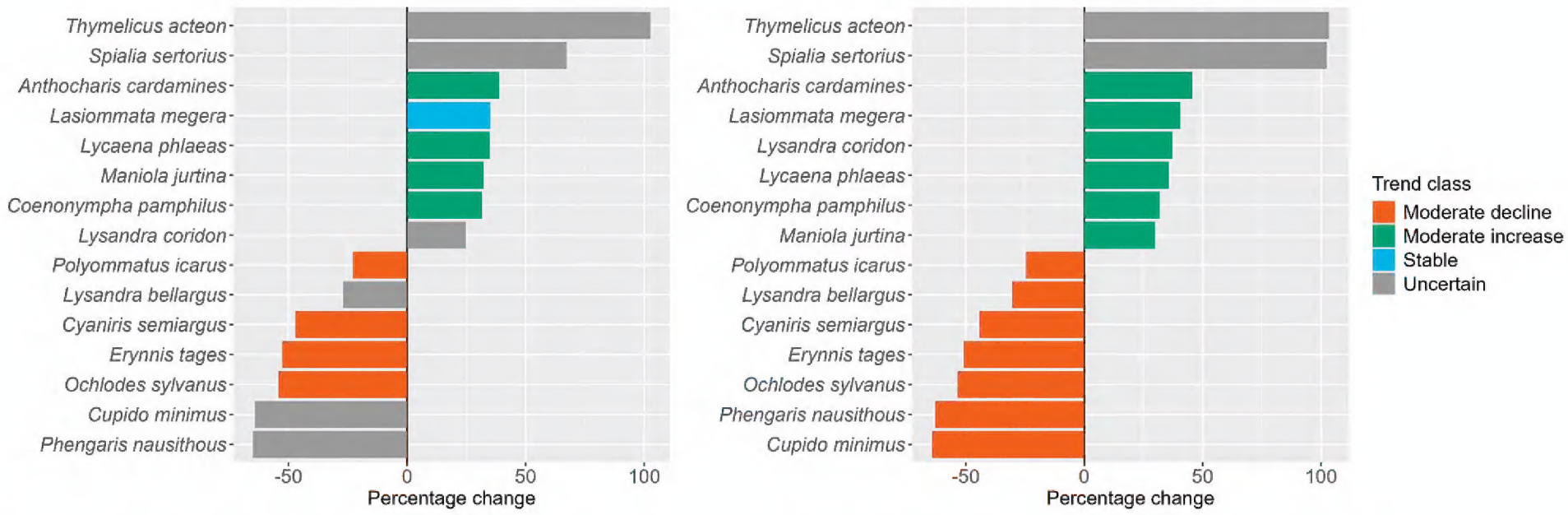

Figure 3. Trends of species included in the German Grassland Butterfly Index. Percentage of change over the entire study period was derived from multiplicative slopes of trend models implemented in Approach 1 (left) and Approach 2 (right). Trend classification follows the scheme by Pannekoek (2005).

Discussion

Trends within the Grassland Butterfly Index in Germany

Depending on the approach, the Grassland Butterfly Index (GBI) in Germany indicated stability or moderate decline from 2006 to 2023. While the Index remained relatively stable in the early years of monitoring, a clear downward trend has emerged in recent years. The decline has been particularly pronounced

over the past decade, when the annual decrease accelerated to -2.82 or -3.26%, depending on the model applied. Thus, the deterioration of grassland butterfly populations apparently has intensified in recent years.

The observed pattern aligns with trends observed in other European countries/regions, such as Sweden (Pettersson and Arnberg 2024), the Netherlands (Van Swaay and Borkent 2025), Luxembourg (Vray et al. 2024) and Catalonia (GENCAT 2024). It also matches the more overarching European Grassland Butterfly Indicator (Van Swaay et al. 2025) when comparing the period from 2006 onwards. These consistent patterns across multiple countries suggest that grassland butterfly decline is not an isolated phenomenon observed in Germany, but rather part of a broader trend driven by common environmental pressures. Amongst the 15 species included in the Index, four showed a significant moderate increase (six when using Approach 2), four exhibited a moderate decline (seven when using Approach 2) and one remained stable. Six species had an uncertain trend (two when using Approach 2). Notably, the species showing positive trends were all widespread generalists, while specialist and generalist species were amongst those declining. The result is in line with previous work indicating more negative trends of specialists in either abundance or occupancy when compared to generalists (Van Swaay et al. 2006; Mattila et al. 2011; Habel et al. 2019b; Fox et al. 2023). It is reasonable to expect that species restricted to certain host plants or habitats will react more sensitively to environmental changes if, for example, their resources are affected. However, classifying species into specialists and generalists is difficult as specialisation rather represents a continuum defined by multiple traits and niche dimensions (Carnicer et al. 2013; Dapporto and Dennis 2013; WallisDeVries 2014).

Potential drivers of decline

Our results do not allow any direct conclusions to be drawn about the drivers of the decline of grassland butterflies in Germany. However, as in many other regions across Europe, factors related to intensive agriculture are likely to be amongst the main causes. For example, intensive mowing has been shown to lower habitat quality for grassland species (Hannappel and Fischer 2020). Some species, such as *Phengaris nausithous*, are known to be particularly sensitive to the timing of mowing. The early instar larvae of this specialist species exclusively feed on the flower-heads of its host plant *Sanguisorba officinalis*. Repeated mowing during this period may reduce population density and finally lead to the extinction of populations, in particular if practised over large spatial scales (Johst et al. 2006). Although there are relatively few valid field studies (Braak et al. 2018) available, pesticides also have a negative impact on butterflies in agricultural areas (Van Deynze et al. 2024).

Habitat quality may not only be lowered by agricultural intensification, but also due to abandonment (Kőrösi et al. 2014; Ubach et al. 2020; Warren et al. 2021). This may be particularly true for species inhabiting less productive habitats where agriculture is not profitable, such as dry calcareous grasslands (Filz et al. 2013a). The GBI also contains species adapted to such environments, such as *Cupido minimus* and *Erynnis tages*, which show or tend to have negative trends. Many factors driving butterfly populations act at the landscape scale, such as habitat fragmentation (Thomas 2016) and landscape homogenisation (Archaux et al. 2018).

Previous analyses using data from the German Butterfly Monitoring Scheme have indicated that the abundance of GBI species is positively related to edge density around transects, indicating that butterflies benefit from heterogeneous landscapes (Kasiske et al. 2024). The loss of small habitats, such as road verges and hedgerows, is therefore likely to lower the opportunities for butterflies to persist in intensively-farmed landscapes. Nitrogen deposition has particularly detrimental effects on species inhabiting naturally nitrogen-poor habitats such as heathlands, bogs and dry grasslands. Exceeding critical loads for nitrogen can alter butterfly community composition, with species preferring nutrient-poor conditions tending to come under pressure (Feest et al. 2014; WallisDeVries and van Swaay 2017; Lebigre et al. 2018). Nitrogen enrichment in host plants due to the input of fertilisers may increase larval mortality of species adapted to nutrient-poor conditions (Kurze et al. 2018). However, a clear relationship between species trends and the nitrogen status of the habitats is not evident, which may also be due to possible interactions with other influencing factors, such as climate change. Climate change has been shown to affect butterfly species, causing latitudinal (Parmesan et al. 1999; Pöyry et al. 2009), altitudinal (Rödder et al. 2021; Habel et al. 2023; Kerner et al. 2023) and phenological (Habel et al. 2024) shifts. In particular, extreme climatic events, such as heatwaves and prolonged droughts, have been identified as significant stressors for butterfly populations (van Bergen et al. 2020; Forister et al. 2021; Shan et al. 2024). The accelerated decline in the German GBI since 2018 coincides with an increase in drought frequency in Central Europe. These climatic effects may interact with habitat-related stressors, exacerbating population declines (Oliver et al. 2015). While the exact mechanisms remain unclear, our findings suggest that grassland habitats are becoming increasingly unsuitable for supporting butterfly populations. In consequence, further research is required on the drivers of butterfly declines. While habitat degradation and climate change are known factors, more targeted studies are needed to quantify the relative contributions of different land-use practices and environmental stressors on the trend of the GBI.

Challenges in defining baselines and targets

The Nature Restoration Regulation (NRR) requires Member States to implement restoration measures until a “satisfactory level” of the indicator is reached (Article 11). However, this term remains undefined, leaving room for interpretation. In contrast, the Farmland Bird Index includes a clear baseline (2025 = 100%) and regional targets ranging from +5% to +30%, depending on past declines. Defining a single-year baseline for butterflies is problematic due to natural interannual fluctuations in population sizes which, in some species, can reach up to several hundred percent. A potential solution would be to calculate a multi-year average baseline to smooth out these variations. Similarly, setting quantitative restoration targets is challenging due to the relatively short monitoring history in Germany (since 2005). Unlike in the UK, the Netherlands and parts of Belgium, where long-term monitoring has shown strong butterfly declines before 2005 (Warren et al. 2021), Germany lacks comparable historical data. However, local and regional studies analysing trends in butterfly abundance (Habel et al. 2019b), occupancy (Engelhardt et al. 2022) or species richness (Filz et al. 2013a, 2013b; Habel et al. 2016) as well as the German national Red

List assessment (Reinhardt and Bolz 2011) also indicate substantial historical losses. These historical losses need to be considered when defining baselines and targets for national restoration planning and reporting for the NRR.

Robustness and representativity of the Index

The reliability of the GBI as an indicator can be enhanced through data harmonisation and the integration of complementary monitoring schemes. Incorporating data from neighbouring countries, as facilitated by the European Butterfly Monitoring Scheme (eBMS) (Schmucki et al. 2016), could improve estimates of species abundance and trends. Additionally, alternative statistical methods for index calculation and bias correction should be explored to minimise potential sources of error. In the present study, we used two approaches to calculate the GBI, both of which are commonly used to calculate biodiversity indices. While the general patterns of the Index over time appear to be very similar between the two approaches, confidence intervals obtained by the bootstrapping procedure are generally wider as compared to those obtained by applying a Monte Carlo simulation. This variation also explains the differences in the significance level of the two trends over the entire period. There are essential differences between both approaches in the way measures of uncertainty are calculated. While the non-parametric bootstrapping approach re-samples site indices from the original dataset, the Monte Carlo approach simulates yearly indices by drawing from a log-normal distribution. Using an ideally simulated dataset, Soldaat et al. (2017) demonstrated that confidence intervals from both methods are almost identical, although those obtained by Monte Carlo simulation were slightly wider. The authors attributed these small differences to stochastic processes inherent in both approaches. In the present study, however, differences were considerably larger and opposite in their direction indicating a generally different performance under real-world conditions. Unfortunately, Soldaat et al. (2017) did not compare the methods using real data and, to our knowledge, respective systematic assessments are not available from the literature. At present, no general recommendation can be given about which approach to use. The Monte Carlo simulation assumes a logarithmic-normal distribution of species indices, an assumption that may not always be valid. Since the bootstrapping approach also works without this prerequisite, it would tend to be preferable. Future work should evaluate under which conditions the various approaches work best. In particular, extreme cases expressed as very large or small population indices, pronounced inter-annual variation and small sample sizes should be given more attention (Soldaat et al. 2017).

There were also differences in the significance of species trends resulting from the approaches applied by Van Swaay et al. (2025) and rtrim by Bogaart et al. (2024), while the direction and magnitude of changes were quite similar. While trend estimation in the first approach is performed using a simple linear model on the bootstrapped collated indices, the second approach uses log-linear models that take serial autocorrelation and over-dispersion into account. Differences mainly occurred in species which are found on a limited number of transects only suggesting a generally lower robustness of these trends due to insufficient data. Further research is needed to optimise models for index calculation and the estimation of trends. This includes a better understanding

of the uncertainty and biases in the Index, but also a critical review of data exclusion criteria and their potential effects on trend estimates. Data from volunteer-based monitoring schemes are typically heterogeneous in quality and contain many missing values. Very strict exclusion criteria may increase confidence in the results, but lower representativeness with respect to species and the spatial and temporal scale covered.

Species selection and regional adaptation

The European Grassland Butterfly Index is based on a standardised set of 17 species, selected for their broad distribution, association with grasslands and suitability for volunteer-based monitoring. However, regional differences in habitat preferences pose challenges for the interpretation of the results (Ubach and Stefanescu 2025). For example, *Anthocharis cardamines* is classified as a grassland species. This is true for regions where it mainly uses *Cardamine pratensis* as larval host plant, occurring on meadows. However, in some regions, such as many parts of Germany, this butterfly species predominantly occurs at forest edges where its alternative host plant *Alliaria petiolata* is more abundant.

This illustrates that species within the Index set may not always serve as accurate proxies for the quality of specific habitats within agricultural systems across all regions. There are several possible solutions to improve the meaningfulness of the Index. First, the species set could be regionally adapted by excluding species that primarily occur outside agricultural systems (e.g. woodland species), replacing them with more representative alternatives. This would improve the specificity of the Index and merely limit the possibilities for comparing the underlying species trends between regions. Nevertheless, species selection remains subjective, as many species cannot be clearly assigned to grasslands or other types of open land. Rather, they can be found in a wide range of different habitats and in the transition zones between them.

As an alternative, index calculation could be restricted to transects located in agricultural systems, ensuring that recorded trends truly reflect the effects of agricultural use and the impacts of restoration measures implemented in these systems. However, without extending monitoring efforts, such restrictions would reduce sample sizes and the statistical power of the analysis.

A possible solution to circumvent the above-mentioned problems would be to apply a new approach recently developed by Ubach and Stefanescu (2025). It includes all species in the GBI for which trends can be calculated, but their contribution to the Index depends on their preference for open habitats. Habitat preference can be quantified by using the TAO Index (Ubach et al. 2020) which reflects the position of a given species along a gradient from closed to open habitats. It is calculated from data on population densities in open and closed habitats which can be obtained from standardised monitoring programmes and habitat maps. Compared to the traditional GBI, a multi-species index weighted by habitat preferences is more specific and it is more representative as it includes all typical grassland species of a given region. Ubach and Stefanescu (2025) showed that the GBI, weighted by preference for open habitats, shows a much steeper decline than the unweighted index, suggesting that grassland butterflies are far more threatened than previously thought.

Limitations and opportunities for improvements

Apart from issues related to the specificity of the Index as outlined above, some other limitations are evident in the dataset, resulting from the structure of the German Butterfly Monitoring Scheme. As volunteers can freely choose the location of their transects, some landscapes and habitat types may be under- or over-represented. For example, a previous analysis has indicated a concentration of transects in areas of high human population density because people prefer counting butterflies in the vicinity of their homes, but not necessarily in either species-poor or species-rich habitats (Kühn et al. 2008). In contrast, habitats of rare species are not well represented in the dataset available through the TMD. This is indicated by the low number of locations for the Index species *Phengaris arion* and *Euphydryas aurinia*, which both had to be excluded from analysis. This problem is also reflected by the uncertain trends of several species, a phenomenon which is likely due to low sample sizes.

To increase the representativity and robustness of the GBI, the necessity to expand monitoring is obvious. This could be done by further investing in capacities for coordination, data management and analysis. In order to improve the availability of data for rare species, it would be worthwhile to develop species-specific monitoring approaches, for example, transects where only the target species is surveyed during its flight period. Furthermore, the data basis for the index calculation could be widened by integrating data from other volunteer-based initiatives as well as professional monitoring schemes, such as the planned federal insect monitoring scheme (https://www.bfn.de/insektenmonitoring) or the monitoring of species of the EU Habitats directives. The latter should enable the calculation of species trends of the index species *Phengaris arion* and *Euphydryas aurinia*. However, data integration and analysis across different programmes may require considerable efforts to harmonise and standardise data collection and to develop workflows along the entire pipeline from data collection to analysis.

Conclusions

The Grassland Butterfly Index provides valuable insights into the state of biodiversity in Germany and serves as an important tool for evaluating restoration success under the Nature Restoration Regulation. However, the observed decline, particularly in the last decade, underscores the urgent need for targeted conservation measures. Addressing challenges related to baseline definition, species selection and monitoring expansion will be important for ensuring the effectiveness of the GBI as a policy-relevant index. Future efforts should focus on improving methodological approaches and fostering synergies between biodiversity monitoring and land management policies to support long-term ecosystem recovery.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

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Data availability

All of the data that support the findings of this study are available in the main text.

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